Strangeness observables and pentaquarks

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Abstract. We review the experimental evidence on firstly, strangeness production as a signature for the QCD phase transition and secondly, pentaquarks, the latest and most exotic manifestations of strangeness in hadrons.

1. INTRODUCTION

The phase transition between deconfined quarks and gluons and hadrons at a temperature of approximately 150-200 MeV is a fundamental prediction of QCD [1]. This phase transition is believed to have taken place in the early universe 10^{-6} sec after the Big Bang. The transition temperature is expected to be reachable with today's accelerators and experimental investigations have tried to induce this transition colliding the largest available nuclei like Pb and Au at ultrarelativistic energies. The experimental searches for the QCD phase transition started in the eighties in AGS, SPS and continue at RHIC while in the future a large experimental program is approved to continue these searches at the LHC and the future GSI accelerator.
Signatures of this phase transition have been measured first at SPS (2000) [2] and then at RHIC (2003) [3]. Among those signatures we remark the suppression of J/Ψ in Pb+Pb collisions above initial energy density ε_i =2.2 GeV/fm^3 [4] (fig. 1 left) as predicted by [5], and the rise and saturation of the chemical freeze-out Temperature (fig. 1 right, from [6]) as a function of collision energy as predicted by [7]. The expectation of a limiting freeze out Temperature is a direct consequence of the assumption of a phase transition in which case T(hadrons) is limited by T_{crit}, and would be expected independent of the concept of Hagedorn's limiting Temperature for a non interacting system of hadrons.
Hadronic reactions have been associated with an underlying thermodynamic behaviour from the fifties [8]. Remarkably, A+A systems at several energies have been found to agree with a grandcanonical ensemble, allowing to define a temperature, and even more remarkably the temperatures at chemical freeze out at $\sqrt{s}$ e.g. 17 GeV were found to be $\sim$ 170 MeV and therefore near T_{crit} [9, 10, 11]. Deviations seen e.g. in resonances are under investigation and can be due e.g. to rescattering of their decay products in the source [12]. Certain colliding systems e.g. the ones taken with minimum bias triggers, do not agree with a grandcanonical ensemble. While we discuss these deviations very briefly, we mainly focus here on strangeness production in colliding systems which agree with a grandcanonical ensemble.

Pentaquarks is a name devoted to describe baryons made by 4 quarks and one antiquark e.g. $uudd\bar{s}$. Exotic pentaquarks have an antiquark with different flavour than

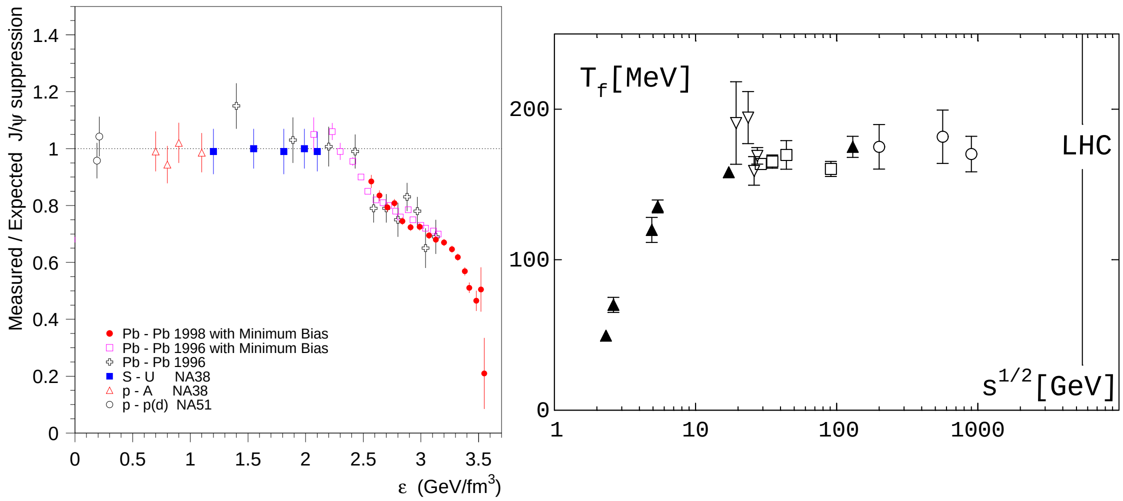

FIGURE 1. Left: J/Ψ suppression as a function of the initial energy density (NA50 Coll.) Right: The freeze out T as a function of $\sqrt{s}$.

their quarks. For recent reviews on pentaquarks see [13, 14]. Pentaquarks have been predicted long time ago e.g. [15, 16] while the number of pentaquark multiplets and their characteristics vary depending on the model used. Figure 2 shows the prediction of a spin-parity $1/2^+$ antidecuplet of pentaquarks within the chiral soliton model [17]. Pentaquark searches were performed already in the 60'ies but few low statistics candidates found have not been confirmed [18]. However, recent significant advances in theoretical [17] and experimental work led to a number of new candidates in the last 2 years of searches [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32].

Both the relevance of strangeness as evidence for the QCD phase transition as well as the evidence for the existence of pentaquarks are unsettled problems. Their clarification will improve our understanding of non perturbative QCD in an important way. QCD, while well understood at high energy scales and small couplings, is less comprehensible at low energy scales and large couplings. Basic questions like what makes up most of the nucleon mass, beyond the small part originating from the Higgs mechanism, search their answer in understanding non perturbative QCD. The confirmation of pentaquarks would break open the over many decades prevailing picture of hadrons as qqq and $q\overline{q}$ constructions only, while another fundamental prediction of QCD namely the existence of glueballs, still strives to be definitively answered. The slow and difficult progress on all the above questions over the years, reflects the fact that the discovery and understanding of both the QCD phase transition as well as of certain rare exotic hadronic states like pentaquarks, hybrids and glueballs represent an enormous experimental and theoretical challenge.

In section 2 we will discuss the initial prediction of strangeness enhancement as QGP signature (2.1), and review the observations, their interpretations and point to some open

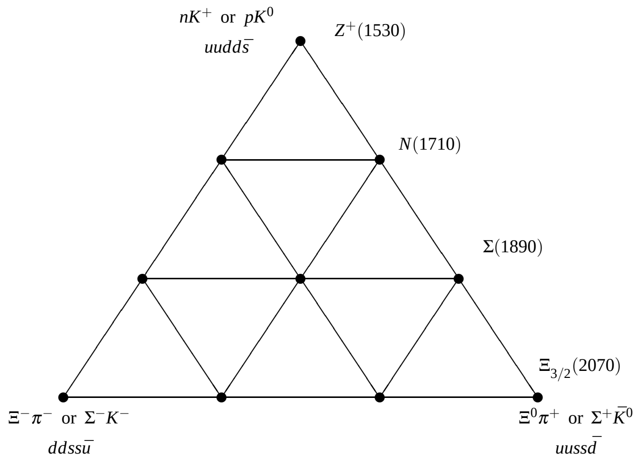

FIGURE 2. Predicted pentaquark antidecuplet with spin-parity $1/2^+$.

questions (2.2, 2.3, 2.4). We address especially the collision energy and energy density dependence of the total $s\bar{s}$ production as compared to light $q\bar{q}$ pairs in colliding systems which agree with a grandcanonical ensemble (2.2). This is then linked to the energy and energy density dependence of the chemical freeze out temperature and ultimately, to the QCD phase transition (2.3). In (2.4) we address briefly some selected topics concerning strangeness in QGP, reflecting work in progress.
In section 3, we review the experimental data on pentaquark candidates, as well as non-observations. We discuss to which extend these sometimes contradicting informations may lead to a consistent picture.

2. STRANGENESS AND THE QCD PHASE TRANSITION

2.1. Prediction: the strangeness enhancement

Hadrons with strange quarks have been predicted to be produced at an enhanced rate out of a Quark Gluon Plasma [33]. $S\bar{s}$ pairs can be produced in the QGP through gluon fusion with a low threshold defined by the mass of the s quark which due to chiral symmetry restoration is decreased to ~ 150 MeV. The mass of the s quark is similar to the transition temperature $m_s \sim T_{crit} \sim 150 MeV$ and strangeness production is expected to reach equilibrium. Multistrange baryons and antibaryons are expected to be even more enhanced out of a QGP because due to their heavy mass they are hardly expected to reach equilibrium in a system below T_{crit}. Therefore the strangeness enhancement is expected to rise with the strangeness content. We will present and discuss in the following selected experimental results focusing on two particular questions: Firstly, if strangeness is enhanced and as compared to what and secondly, if there is experimental evidence for the QCD phase transition from strangeness production.

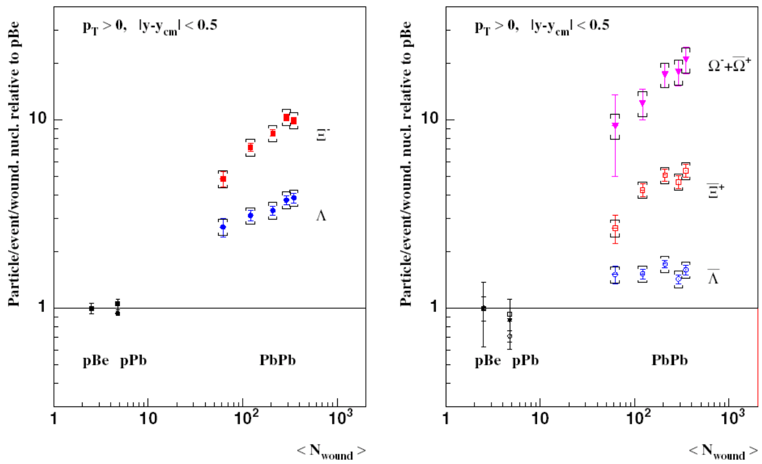

FIGURE 3. Particle yields in Pb+Pb collisions at $\sqrt{s}$=17 GeV from the NA57 experiment shown per participant nucleon N, as a function of N. The ratios have been normalized to the same ratios in p+Be collisions at the same energy also from NA57.

2.2. Is strangeness enhanced and as compared to what?

The first measurements and first definition of strangeness enhancement

Historically, strange particle production has been measured in several collisions of heavy nuclei (A+A) and has been systematically compared to p+p, p+A or peripheral A+A collisions at the same energy. The collisions of elementary particles like p+p or of peripheral A+A collisions have been taken in the literature as a reference system, that is they have been assumed to represent a colliding system in which no phase transition takes place because the volume is too small. In this case the p+p system is not expected to reach equilibrium.

The first observation of a K/π enhancement was reported in 1988 in central Si+Au collisions at E_{beam} 14.6 A GeV [34]. The first observation of a Λ, $\overline{\Lambda}$ and K_s^0 over pion enhancement in A+A was reported in 1991 in central S+S collisions at E_{beam} 200 A GeV, compared to peripheral S+S and p+S collisions [35]. These first results were followed by a vast number of other observations of strangeness enhancement, e.g. [36].
Therefore the 'strangeness enhancement' has been first observed and defined as an enhancement of the double ratio of strange particles over pions in central A+A collisions as compared to p+p, p+A or peripheral A+A collisions at the same energy.

Strange baryons and antibaryons

A spectacular later finding was the enhancement factors up to 20 which have been measured for multistrange (anti)baryons (Ξ, $\overline{\Xi}$, Ω, $\overline{\Omega}$) in Pb+Pb collisions at $\sqrt{s}$= 17 GeV as compared to p+A collisions at the same energy (figure 3) [37]. While Ξ production at AGS [38] is well described with hadronic models this is not the case at SPS energy [39]. It is seen that the enhancement rises with the strangeness content. The 'strangeness enhancement' has been defined here as ratio of strange particle to the number of participant nucleon (N) in Pb+Pb as compared to p+A collisions at the same energy.

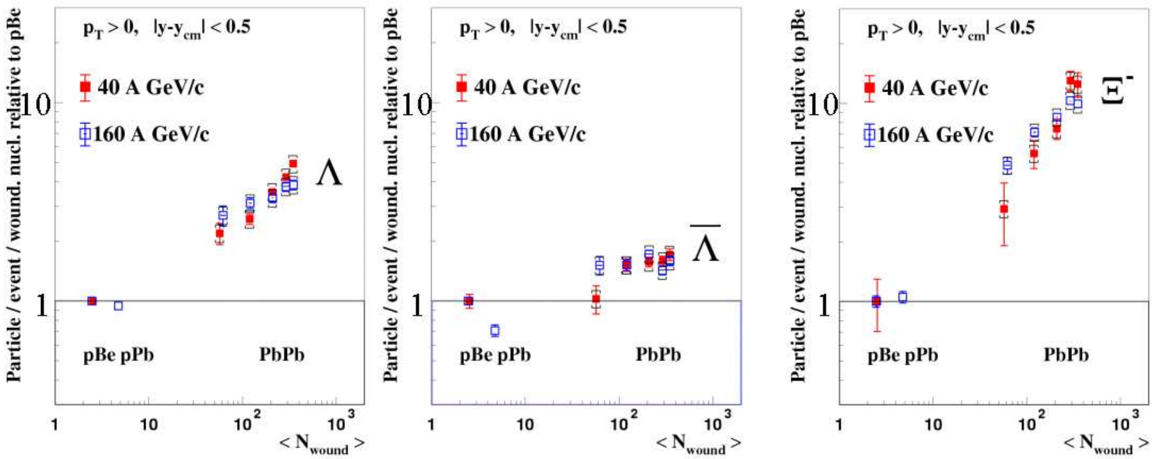

FIGURE 4. Particle yields per participant nucleon N, as a function of N in Pb+Pb collisions at $\sqrt{s}$=17 and 8.8 GeV from the NA57 experiment. The ratios have been normalized to the same ratios in p+Be collisions at the same energy also from NA57.

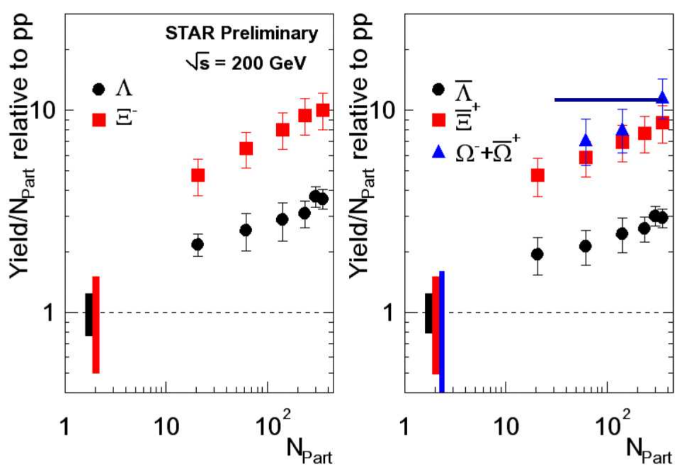

FIGURE 5. Particle yields in Au+Au collisions at $\sqrt{s}$=200 GeV from the STAR experiment shown per participant nucleon N, as a function of N. The ratios have been normalized to the same ratios in p+p collisions at $\sqrt{s}$=200 GeV also from STAR.

Another remarkable observation is that the yield of Ξ and Λ remains constant in $\sqrt{s}$= 8.8, 17 and 200 GeV [40]. This may originate from a connection of strange baryons to the initial baryon number. It may however also be an artifact of the phase space acceptance of the measurement and the different baryon distributions at SPS and RHIC, as many strange baryons are expected where the baryons are abundant e.g. at forward rapidities. This can be studied with Λ's in the FTPC of STAR and BRAHMS forward K data [41].

N dependence

Baryons as Ξ, Λ and Ω (the sum Ω+$\overline{\Omega}$ at this energy represents mainly the Ω's) per participant N in Pb+Pb at 158 A GeV rise with N, while antibaryons ($\overline{\Xi}$, $\overline{\Lambda}$) show a

saturation in the most central bins (fig. 3). This saturation maybe due e.g. to antibaryon annihilation in the highest densities. Since particle yields per N is approximately proportional to number density, assuming that N is proportional to the Volume (which may be incorrect due to expansion) in equilibrium particles per N should be N indepandant. Therefore a rising particle per N ratio versus N could be interpreted as a deviation from equilibrium [42].
The rise and saturation of particle densities with increasing volume as seen in the antibaryons, has been described as due to the gradual change from a canonical to a grandcanonical equilibrium description e.g. [43][1] However, the latter two cases should be visible in the baryons too, not only in antibaryons which is not the case.
Another possibility is that the change of density with N is due to a rise of temperature [42] and not to deviations from full equilibrium, assuming that an equilibrium description is valid for each of those N points to be able to define T.
The rise of particles per N with N may be attributed to hard collisions. However, the rise of particles per N with N seems steeper at 40 GeV than at 170 GeV Pb+Pb collisions (fig. 4). If the deviation from flat behaviour was due to a hard component, it should increase with energy. Therefore the rise seen in 40 and 170 GeV PbPB is not due to a hard component in strangeness production at these energies.
At RHIC (figure 5) one observes a continous rise of particles per N [44]. The $\overline{\Lambda}$ do not saturate, neither the $\overline{\Xi}$. At RHIC one may expect hard processes to manifest themselves and this can be investigated looking at the p_T spectra and the N^{α} dependence of particles and comparing to lower energies and to models.
In conclusion the strange baryons per N rise with N at all energies ($\sqrt{s}$= 8.8, 17 and 200 GeV). Antibaryons do so only at RHIC, while at lower energies show saturation. The latter can be understood as due to antibaryon annihilation. The understanding of the N dependence of strange and non-strange particles is an open issue which needs more data and theoretical work to be understood.

Is the observed enhancement as expected for the QCD phase transition ?
The enhancement factors of strange baryons and antibaryons are slightly smaller at $\sqrt{s}$= 17 GeV than at 8.8 GeV, and are smaller at $\sqrt{s}$= 200 GeV (STAR) than at 17 GeV (SPS), with the exception of $\overline{\Lambda}$. This exception maybe due to annihilation effects and the different μ_b leading to a larger $\overline{\Lambda}/\Lambda$ ratio at RHIC. We therefore observe, that the enhancement factors of strange baryons and antibaryons per N in Pb+Pb as compared to p+A at same energy seem to decrease with increasing energy.
Figure 6 left shows that the K/pi ratio in A+A over p+p collisions [45] is as well increasing towards lower energies. Why is that so? We will address this question at the end of section 2.2.

Remarkably, this behaviour is exactly opposite to the theoretical expectation that $s\bar{s}$ enhancement is induced with increasing T and collisions energy, namely at or near Tc.
This disqualifies the strangeness enhancement definition as enhancement in central A+A

[1] In this work, with "canonical" describtion it is meant that the system did not yet reached the thermodynamic limit at which all ensembles are equivalent.

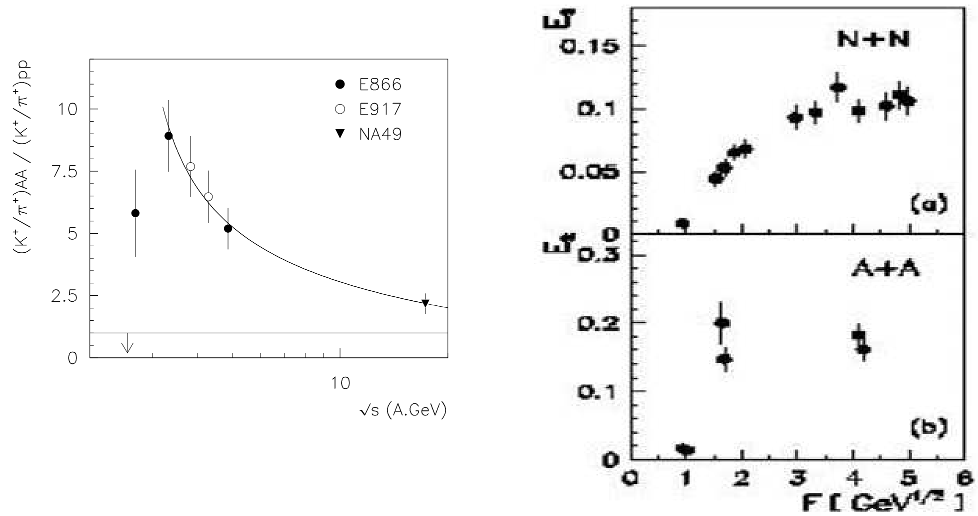

FIGURE 6. Left: Double ratio of kaon to pion in A+A over p+p collisions as a function of energy. Right: $E_s = (\Lambda + K)/\pi$ ratio as a function of energy (F=f($\sqrt{s}$).

collisions over p+p or p+A collisions at the same energy, as a QGP signature.

Energy dependence of strange to pion ratio in A+A collisions

Another approach to study strangeness production relative to light flavours (u,d) is to look at the energy dependence of strange to non strange particles in the same kind of reactions e.g. nucleus+nucleus and particle collisions separately. The first such study [46] has shown that the energy dependence of strange particle to pion ratio (E_s) is different in A+A and N+N collisions. They observed a rise and subsequent saturation of E_s with energy (fig. 6, right). The authors proposed that the increase of strangeness over pion ratio at low energies is a consequence of the strangeness over entropy ratio being proportional to the chemical freeze-out temperature, which rises with collision energy. They observe a maximum of E_s in A+A, unlike p+p collisions, and they interpret this as due to the onset of the phase transition taking place between AGS and SPS near the maximum of E_s [47] which had yet to be localized at that time.

Maximum of strange/pion ratio at 30 GeV Pb+Pb collisions

In the mean time, the maximum seen in E_s has been confirmed dramatically through latest data from NA49 [48]. NA49 found a maximum at 30 GeV Pb+Pb collisions (figure 7, 8) however only in K^+/π^+, Λ/π, while no maximum is seen in K^-/π^- which rises continouisly with energy (figure 7 right). Since a high baryon to antibaryon ratio favours the associated production of ΛK^+ the above differences suggest that they may be connected to the different baryochemical potentials μ_B reached at different energies in the same collision system (Pb+Pb, Au+Au) near midrapidity.

The baryon to antibaryon ratio is continouisly droping with decreasing energy in the same A+A system (e.g. [40]). Which implies that the K^+/π^+ and Λ/π ratio should continouisly rise with decreasing energy. Why is this not the case? Because the temperature drops below a certain energy (figure 1, right) and all ratios reflect this fact.

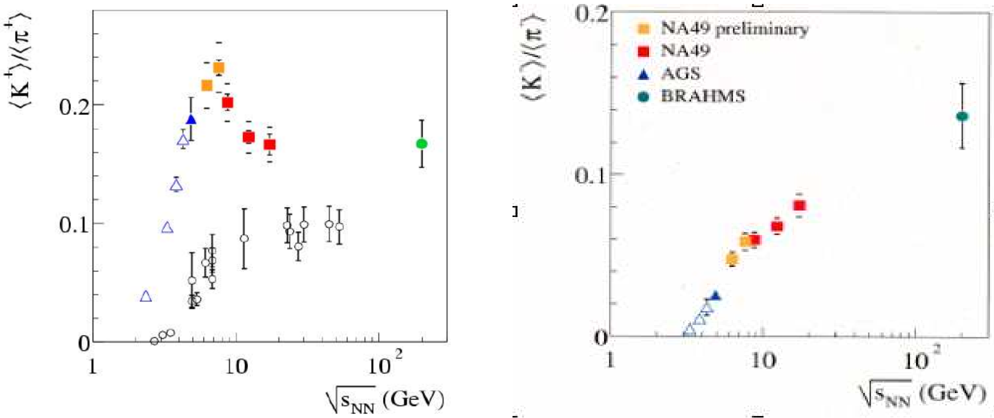

FIGURE 7. Left: K^+/π^+ ratio as a function of $\sqrt{s}$ in several reactions. Right: K^-/π^- ratio as a function of $\sqrt{s}$ in several reactions.

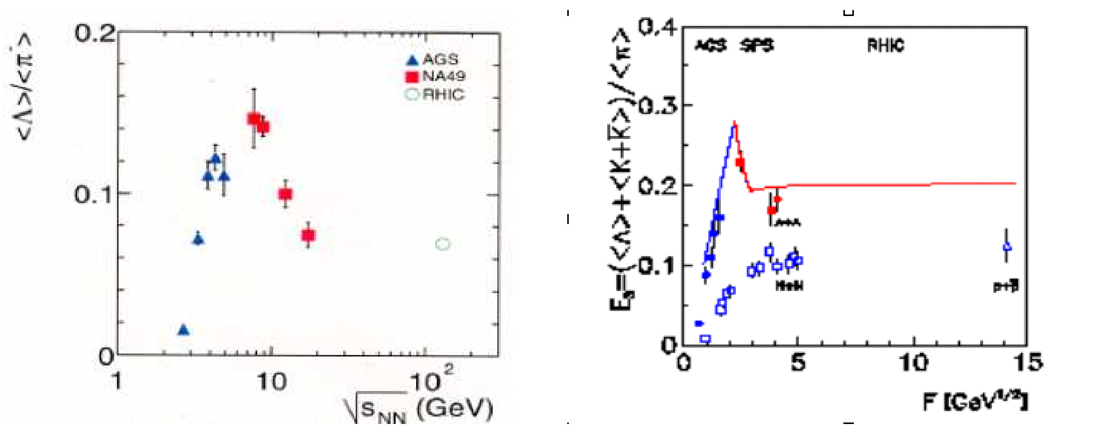

FIGURE 8. Left: Λ/π ratio as a function of $\sqrt{s}$ in several reactions. Right: E_s factor as a function of $\sqrt{s}$ in several reactions. See text for more explanations.

The hadronic models URQMD and HSD underestimate the K^+/π^+ ratio but do reproduce well the Λ/π ratio and it's maximum [49]. To understand this discrepancy one could investigate the sharing of $s\bar{s}$ among hadrons, check conservation of $s\bar{s}$ and study the dependence of major channels like K^+K^- and ΛK^+ from collision energy, stopping and baryon density. For more discussion of hadronic models see e.g. [39, 49].

The maximum of the strange to pi ratio near 30 A GeV Pb+Pb collisions as mentioned previously has been interpreted as due to the onset of the QCD phase transition. Figure 8, right shows the prediction of [47].

However, this maximum has been explained in the mean time as a consequence of different μ_B values.
The influence of a varying μ_B in the energy dependence of strange to pion ratios has been investigated for the first time in [10, 50]. Each of the studied thermodynamic systems has

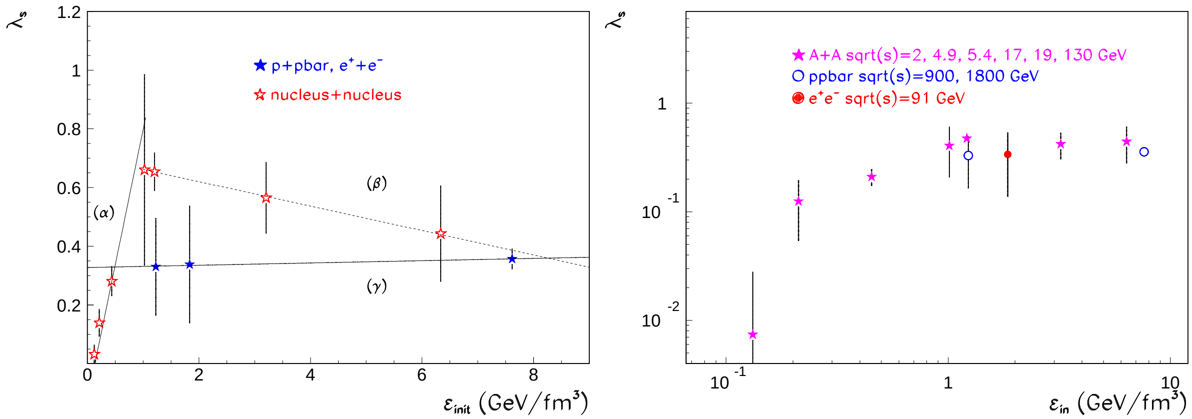

FIGURE 9. Left: Strangeness suppression factor λ_s as a function of the initial energy density in several reactions. Right: the same as left, after extrapolating all points to $\mu_B = 0$.

been extrapolated to the equivalent thermodynamic systems at zero chemical potential. This is equivalent to an extrapolation of e.g. all Pb+Pb collisions to $Pb+\overline{Pb}$ collisions. The strangeness suppression factor λ_s, defined as the ratio of newly produced $s\bar{s}$ to light newly produced $q\bar{q}$ ($\lambda_s = \frac{2s\bar{s}}{(u\bar{u}+d\bar{d})}$) [51], is maximal in Pb+Pb collisions at 40 A GeV (figure 9, left, point at the maximum of the triangle). However, after the difference in the μ_B of the two systems is eliminated λ_s is found to be the same at 40 and 158 GeV (figure 9, right). Therefore the difference in strangeness is explained as due to the higher μ_B in 40 GeV as compared to the 170 A GeV Pb+Pb collisions.

If a part of the K/π enhancement is due to the onset of the QCD phase transition and a part to the high baryon density, the extrapolation to zero potential of all systems [10, 50] should leave a residual enhancement due to the phase transition itself. Figure 9, right, shows no such enhancement. This means that the enhancement seen in the K/π and Λ/π ratios at 40 GeV Pb+Pb collisions (figure 8, 7) has nothing to do with the phase transition. One should look if a peak appears after eliminating the μ_b with more data at 20 and 30 GeV (SPS) and around that energy at the future GSI. This has not been studied yet. The experimental measurement of many particle ratios at 20 and 30 A GeV Pb+Pb collisions by NA49 is therefore important for the understanding of this maximum.

The same conclusion that the 'maximum' of strange to pion ratio is driven by the baryons has been reached later by [52]. The (T,μ_B) points describing colliding systems were found interestingly to be fitted with a curve assuming constant energy per hadron at freeze out $< E > /N \sim 1$ GeV [53] (fig. 10, left).
Figure 10, right, shows that this parametrization, while it describes the general trend of the strangeness suppression factor versus energy, it does not fit in detail the λ_s e.g. at SPS. In addition there is no pronounced peak but a broad maximum.

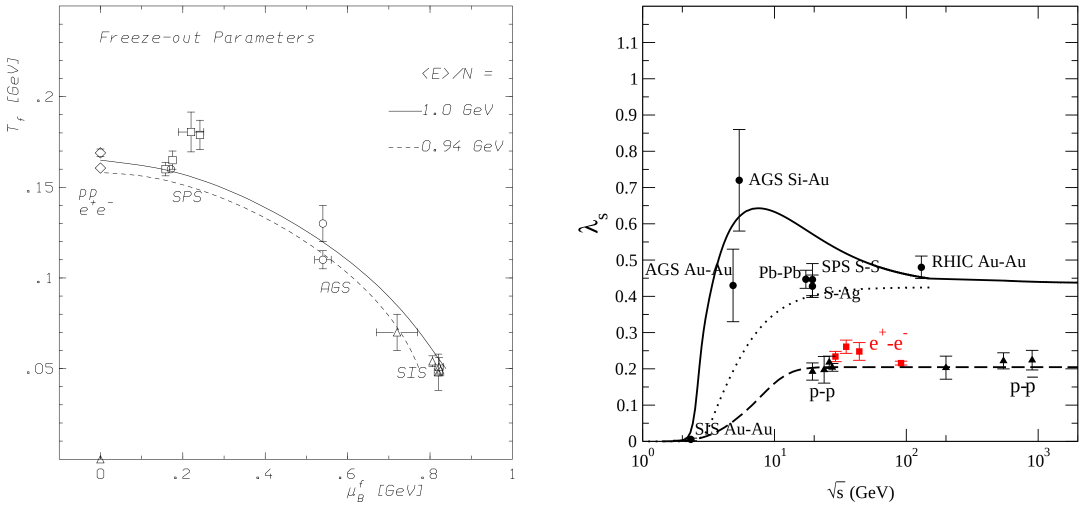

FIGURE 10. Left: T versus μ_B. Right: λ_s versus energy. See text for explanations.

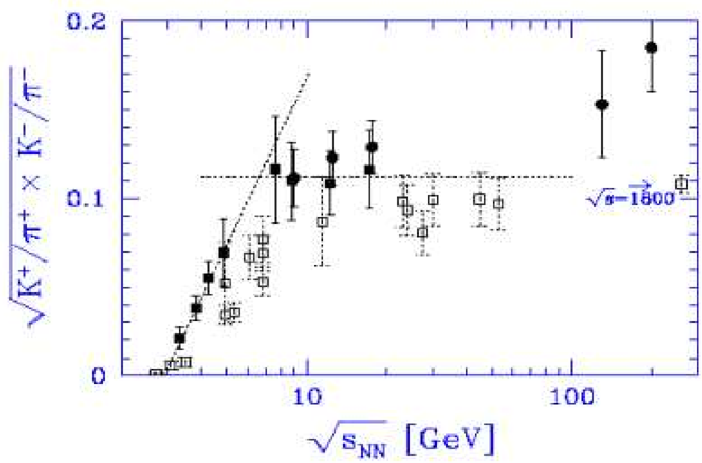

FIGURE 11. The quantity $\sqrt{(K^+/\pi^+)(K^-/\pi^-)}$ as a function of energy.

However, one should not conclude from this, that thermal models do not reproduce the maximum. The lack of a pronounced maximum is not due to the thermal model since the 30 and 40 A GeV points are well described by thermal model fits [54, 50, 55]. The less accurate description of the energy dependence of λ_s and the lack of a sharp maximum, may be due to the fact that the parametrization of a constant $< E > /N \sim 1$ GeV does not describe well the ratio of strange to light quarks λ_s. Note that the ratio $< E > /N$ is not a constant but exhibits a change in other thermal model analysis (fig. 14 of reference [50]).

In another study, the ratio $\sqrt{(K^+/\pi^+)(K^-/\pi^-)}$ is found to rise and saturate with increasing energy while increasing at RHIC energy [56] (figure 11). This ratio is special, as it constructed in such a way that it is μ_B independant. The lack of any maximum near 40 GeV Pb+Pb strengthens the previous conclusion that the maximum is due to the

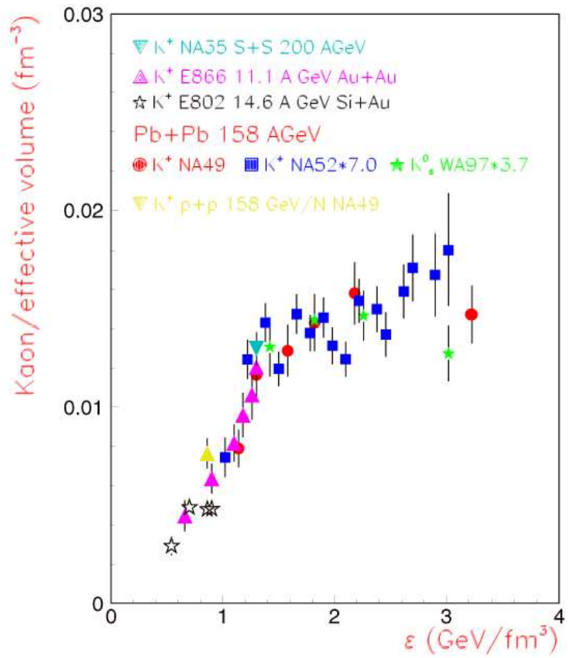

FIGURE 12. Ratio of kaon yields per effective Volume as a function of the initial energy density for several reactions.

different μ_B [50, 52].

In [56] the higher K/π at RHIC is discussed as possibly reflecting a 'strangeness enhancement', seen only in Au+Au collisions at RHIC as compared to $p+\overline{p}$ collisions (fig. 11). There are two things to mention. Firstly, since the share of $s\overline{s}$ among hadrons changes with energy one should look at the total strangeness production (λ_s) versus energy.
When one does this, looking at the λ_s at $\mu_B = 0$ (fig. 9, right) this enhancement dissappears.

Strangeness in $p\overline{p}$ collisions at the Tevatron is similar to Au+Au at RHIC?
Secondly, the point for $p\overline{p}$ collisions at $\sqrt{s}$ = 1.8 TeV (last open rectangular point to the right) in figure 11 is for a minimum bias trigger. The minimum bias point is below the points for central Au+Au collisions at RHIC.
However, for $p\overline{p}$ collisions at $\sqrt{s}$ = 1.8 TeV with the highest charged multiplicity, one finds that the resulting K/π ratio of 0.14 ± 0.2 is consistent with the RHIC Au+Au data shown in fig. 11 [10].
In addition the λ_s from a grandcanonical fit with good χ^2/DOF to these data is consistent with the λ_s at RHIC when the different μ_b are eliminated [10] (fig. 9, right). While the minimum bias $p\overline{p}$ collisions at $\sqrt{s}$ = 1.8 TeV do not agree with a grandcanonical fit.
These findings call for more measurements of particle ratios in $p+p$ and $p+\overline{p}$ collisions at the Tevatron and the LHC.

Strangeness enhancement is due to a canonical to grandcanonical transition?
It is discussed recently in the literature that within statistical models the enhancement of strangeness in A+A is the result of volume dependant canonical strangeness suppression in p+p, p+A and possibly minimum bias A+A collisions.
This is not really true, because even if the p+p and A+A systems were both grandcanonical, the strangeness would be still enhanced in A+A as compared to p+p collisions, if e.g. μ_b and/or the initial reached T and ε differ.
At the same colliding energy p+p , p+A and A+A collisions (assuming we can use thermodynamic language to describe them and we do that when thermal model fits work well) form systems with different thermodynamic properties: different baryochemical potentials, different temperatures and different energy densities. Comparing therefore A+A to a p+p or p+A collision at the same energy may be like comparing apples and oranges. This explains why the K/π ratio in $A+A$ over $p+p$ collisions increases with decreasing collision energy as seen in fig. 6, left.

Comparing the same A+A collision system at different energies, may also be like comparing apples and oranges. For example, we have seen that the higher strangeness content in 30 and 40 GeV Pb+Pb as compared to 158 is due to the different μ_B [50, 52, 56]. This has nothing to do with a phase transitiion.

The above thoughts lead us to formulate some questions:

- Is there a strangeness enhancement beyond trivial sources causing strangeness enhancement like a higher μ_B ?
- Should we compare different colliding systems at the same colliding energy or choose a more relevant common parameter or set of parameters ?
- Which should be this parameter ?
- Is there a strangeness enhancement in A+A over p+p collisions when they are compared at the same value of this parameter ?

We will address these questions in the following section.

2.3. Do we see evidence for the QCD phase transition from ssbar production?

The choice of the 'gauge' parameter for comparing strangeness
A natural choice for the 'gauge' parameter would be the initially reached temperature. We cannot measure this quantity. The only quantity characterizing the intial state of the colliding system which can be estimated from measurements is the initial energy density ε_i.
The first study of strangeness production as a function of the initial energy density has been performed in [42]. It was found (figure 12) that looking at the ratio of Kaon per participating nucleons not as a function of participant nucleons, but as a function of ε_i

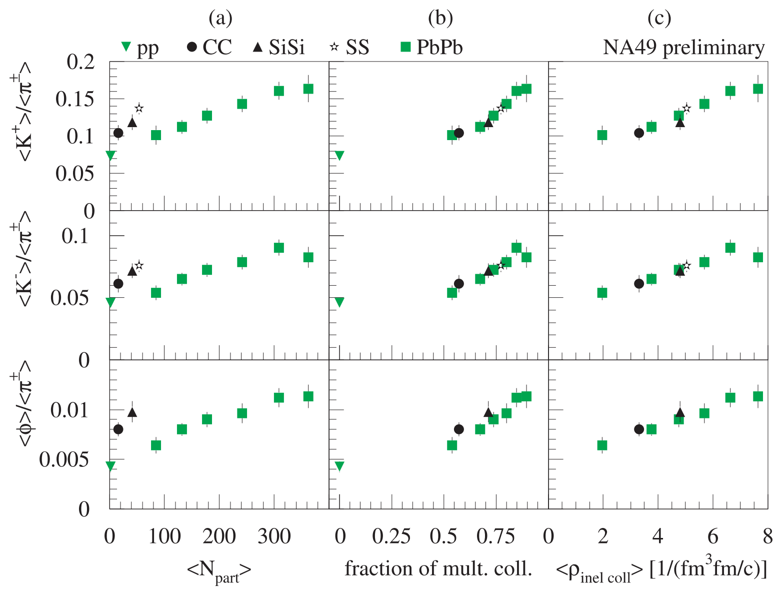

FIGURE 13. Ratios of strange particles to pions as a function of the number of participant nucleons, of collisions and of the space-time density of inel. collisions, by the NA49 Collaboration.

transforms the puzzle of different N dependences seen in different energies and looking incoherent, into a universal curve throughout the different collision systems (fig. 12).
Most importantly it rises with ε_i and saturates at the vicinity of $\varepsilon_i \sim 1$ GeV which corresponds to 40 GeV Pb+Pb, therefore showing a dramatical change near $\varepsilon_e \sim 1$ GeV/fm^3. This onset of strangeness saturation is at a lower ε_i than the onset of J/Ψ suppression of 2.2 GeV/fm^3 (fig. 1) which maybe due to the fact that J/Ψ suppression may be overcritical (e.g. [57]).
No maximum is seen in figure 12, for the reason that the data near $\varepsilon_e \sim 1$ GeV are not taken from 20, 30 and 40 GeV Pb+Pb collisions but are all from 158 GeV Pb+Pb collisions. Therefore the μ_B does not change dramatically in the above figure.
Note that kaons in fig. 12, behave like antibaryons in fig. 3, right. Mesons and antibaryons are less directly related to the initial baryon number than baryons and their characteristics may deviate. We also mentioned antibaryon annihilation.
However, what is really relevant to study is the overall $s\bar{s}$ trend.

Initial energy density dependence of λ_s

The first study of the overall $s\bar{s}$ production as compared to newly produced light quarks (λ_s) as a function of ε_i has been performed in [10, 50]. The λ_s factor shows a rise, a maximum and subsequent decrease with increasing ε_i (figure 9, left). The λ_s factor for A+A collisions is higher than the one for p+p and $p\bar{p}$ collisions.
However, after extrapolating all thermodynamic systems to μ_B=0, the factor λ_s shows a universal behaviour: it rises and saturates above $\varepsilon_i \sim 1$ GeV/fm^3 (fig. 9, right). This behaviour is followed by both A+A as well as by some particle collisions like 'central' $p\bar{p}$ collisions which give a good thermal fit. The central Tevatron $p\bar{p}$ collisions give as

mentioned the same λ_s as central Au+Au at RHIC within errors. A small remaining systematic deviation of the T and the λ_s being somewhat smaller in e^+e^-, $p\overline{p}$ and p+p collisions as compared to central A+A collisions at μ_B=0 [10], maybe attributed to volume effects.
Practically all the enhancement of A+A over p+p collisions seen in fig. 9, left, dissappears at same μ_B (fig. 9, right).

Why is the extrapolation to μ_B=0 important and what we learn from that, is discussed in the next session.

The use of other scale factors like the mean space-time density of all inelastic collisions during interpenetration fo the nuclei ($< \rho_{inel.coll.} >$) also leads to a better agreement of ratios in different A+B collisions at the same energy (fig. 13, middle and right), which differ when studied as a function of N (fig. 13, left) [58]. However this choice of scale factors e.g. the density, does not account for the different energy and therefore does not allow the comparison of collisions with different energies. The latter is possible using the initial energy density, which includes the energy dependence.

The extraction of critical parameters

Assume we heat water, and measure the temperature versus the heat, but we are not allowed to measure the temperature of the steam (analogy to QGP) but only of the water (analogy to hadronic system). We would measure a rising temperature and then a saturation just below 100 ^0C, at normal density and pressure for water, because after T_{crit} is reached, we always measure the water temperature below T_{crit} even if heating is increased. From the plot we can find the T_{crit} for this phase transition, as the limiting T at which the T versus heat saturates namely 100 ^0C. This idea has been proposed long time ago [7].
Would we now put inside the water some salt and repeat the experiment we would each time find a different limiting T at saturation depending on the water salinity. Studing systems with different baryochemical potentials is like studing systems with different salinities and searching for the limiting temperature. In order to measure a single limiting temperature we should make the experiment at the same salinity.
The simplest way to normalize nuclei and particle collisions to the same 'salinity' (μ_B) is to take salinity (μ_B) zero. One may then plot the chemical freeze out T as a function of the initial energy density and find the phase transition temperature without involving a comparison to theoretical predictions. This method has been proposed in [59] and was performed in [10] and [50]. The result is as expected a rise and saturation (fig. 14).

We learn (figure 14) that the onset of the QCD phase transition extracted from the onset of T saturation can be estimated to be $\sim$ 1 GeV/fm^3. [10]. A more precise estimate leads to 0.6 $\pm$ 0.2 (stat) $\pm$ 0.3 (syst) GeV/fm^3 [60]. This value is independent of lattice QCD predictions. The extracted $\varepsilon_{i,crit}$ is in agreement with the predicted lattice QCD values [1].
Furthermore, we learn that the temperature does not depend on the μ_B as sensitively as the λ_s, as the plots of T versus energy or energy density with different μ_B's (fig. 1,

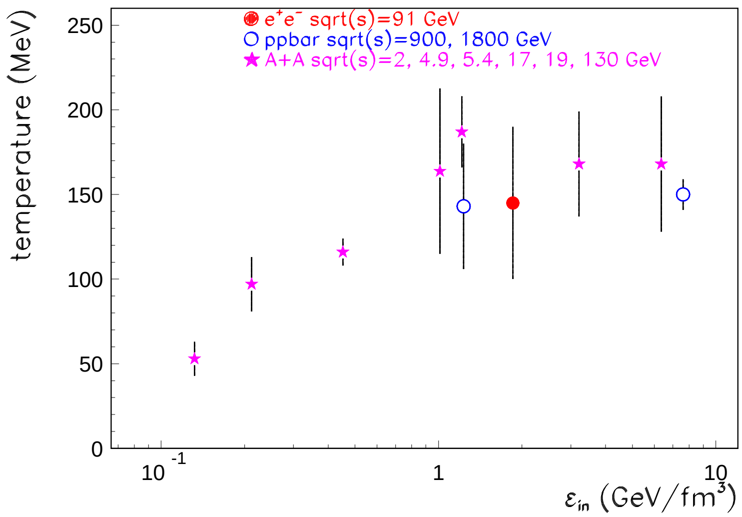

FIGURE 14. Left: Temperature as a function of initial energy density for several systems at $\mu_B = 0$.

right) and with the same μ_B (=0) (fig. 14)) are very similar. This is why the plot of T versus collision energy at different μ_B, does not show any maximum near energy density 1 GeV/fm^3 (fig. 1, right).
On the contrary we have seen that strangeness is very sensible to different μ_B, it is a real 'baryonometer' as well as a real 'thermometer", as it depends much also on T.
A rising μ_B with decreasing energy would simply enhance λ_s continuously, (e.g. λ_s would continue to rise also below $\varepsilon_i \sim 1\ GeV/fm^3$ in fig. 9, left), would not be the case of the T falling below a certain limit (namely exactly at $\varepsilon_i \sim 1\ GeV/fm^3$, fig. 14).
From the extrapolation to μ_B=0 we learn that the λ_s factor at μ_B=0 (fig. 9, right) shows no maximum anymore but it simply and universally follows the T in its rise and saturation versus initial energy density (fig. 14). This seems to be the case for A+A and also for $p+p$ or $p\overline{p}$ collisions as suggested by fig. 9, while more data are needed to study λ_s in the latter in detail.

Where is the strangeness enhancement and as compared to what ?
Strangeness enhancement can be therefore reinterpreted as the λ_s enhancement seen in all colliding systems which give a good thermal fit and have a ε_i higher than approx 0.6- 1 GeV/fm3 as compared to all colliding systems which either give no thermal fit or which have an ε_i smaller than 0.6- 1 GeV/fm3 (fig. 9). Therefore the definition of 'reference no QGP system' is changed in a dramatic way, as well as the notion of 'strangeness enhancement'.

Can we measure the approach to T_{crit} and the critical exponent ?
In addition, using parameters characterizing the data at $\mu_B = 0$ one can study their approach to T_{crit} (as usually done in physics of other phase transitions) and extract the latter as well as the critical exponent. The approach to T_{crit} has been fitted with a

function $f = const/ln(1-T/T_{crit})^{\alpha}$ for the first time in [50] using only data with $\varepsilon_i > 1$ GeV/fm^3. It was found a T_{crit}= 218 $\pm$ 70 MeV and a critical exponent α=0.54 $\pm$ 0.47. The errors are very large in this study which only demonstrates the principle. LHC and RHIC data may allow to study in detail the approach to T_{crit} in this way. It has been further predicted that the λ_s factor in A+A collisions will reach practically its limiting $\mu_B = 0$ value at the LHC [50].

How can equilibrium be reached in high energy particle and nuclear collisions ?
It is an ongoing discussion in the literature what the saturation of the chemical freeze out T with increasing energy really means (fig. 1, right) and in particular why is the same for e^+e^-, p+p and A+A collisions e.g. [61, 62, 63].
It is always taken for granted that no QCD phase transition can appear in a p+p system due to the small volume. What if the p+p system has infinite energy ? After which energy the initially colliding particle volumes plays no role anymore ?
Maybe it is not a completely unexpected feature, if the hadronization of any quark and gluon system into hadrons (e.g. jet hadronization), as well as the hadronic mass spectrum, do reflect the existance and value of the T_c of the QCD phase transition. Speaking about temperature, we assume implicitly thermal equilibrium. Could jet hadronization be a thermodynamic process?
If a grandcanonical ensemble can describe the ratios in a $p\overline{p}$ collision and a temperature can be defined, why not a "QCD phase transition" in a high multiplicity $p\overline{p}$ collision ? [64] Along a hadronizing jet ? [65].
While $q\overline{q}$ produced in an elementary collision fly apart and cannot communicate with each other [62], the hadronization along each jet and the resulting particle yields may exhibit equilibrium features reflecting the T_c.
Does the QCD vacuum itself have a thermostat-like nature [62] ?

However, fact is that like A+A collisions, also elementary collisions do not always agree with a thermal model. In particular $p\overline{p}$ collisions, like A+A collisions too, need a "centrality" trigger to result in grandcanonical particle ratios e.g. at midrapidity.
How can a high multiplicity $p\overline{p}$ collision appear to be an equilibrated system? The importance of quantum mechanical coherence for several aspects of multiparticle production in high energy particle and nuclear collisions has been discussed in [62] and [63].
High energy particle and nuclear collisions should not be viewed as a classical billiard ball cascade. Interactions among particles and virtual particle exchange for a quantum mechanical coherent system may lead faster to equilibrium and therefore to the equilibrium particle ratios pattern which is observed for the final (incoherent) particle species emmitted and observed in the detectors. This is true for nuclear as well as for particle collisions at high energies.

In the following, we address very briefly some topics of interest without going into detail.

2.4. Selected topics

Selected topics: 1. Studies of deviations from equilibrium
Many interesting studies have been performed searching for deviations from equilibrium in particle production by introducing new parameters like a correlation volume or a factor γ which measures deviation from equilibrium of a certain particle type e.g. [66, 43, 56]. Such studies are very interesting and promising.

However even if the introduction of free parameters like γ factors for pions and/or strange particles is improving the fits, the physics interpretation of the result may not be unique.
For example the same deviation of measured ratios from a thermal source can be interpreted as strangeness nonequilibrium, or as pion nonequilibrium or both, or baryon nonequilibrium and so on, and have each time a better chisquare than a grandcanonical fit, while the deviation may even be due to something else e.g. to an incorrect resoncance decay correction.
It is also unclear if the precision of the measurements and in particular the correction for resonance decays is good enough for such studies. The systematic errors of those corrections should be smaller than the deviations seen in the data. More precise data from RHIC and LHC will help such studies to really explore their potential.

On the other side, standard thermodynamics (namely when there is no distinction between grandcanonical ensemble and other ensembles) therefore with no gamma factors, allows for a conceptually clear interpretation of the thermal or not thermal nature of a particle source. It is also found that indeed can fit a large variety of data with a good chisquare [9, 10], including high multiplicity $p\overline{p}$ collisions [10].
Particle yields from $p+p$ and $p\overline{p}$ collisions at highest energies are very limited. It is therefore very important to achieve a better understanding of hadron production and strangeness in particular in p+p and other particle collisions through more measurements and theoretical work like e.g. [67].

Selected topics: 2. The ϕ
The puzzle of different characteristics seen between the channels $\phi \rightarrow e^+e^-(\mu^+\mu^-)$ and $\phi \rightarrow K^+K^-$ possibly due to rescattering of Kaons, is under experimental investigation [68, 69, 70, 71, 72]. It seems that the discrepancy in the ϕ yield may be reduced using a new estimated branching ratio, however the different p_t slopes still remain. No discrepancy is seen in d+Au at RHIC by PHENIX [69].

Selected topics: 3. The role of Isospin corrections
Another interesting new experimental finding is the fact that after correcting for the isospin the ratio K^+/π^+ in Pb+Pb over p+p is similar to the same ratio in p+Pb over p+p [73]. It would be however interesting to see the isospin corrected overall λ_s in full phase space or at midrapidity, rather than only one particle ratio, to be able to draw conclusions. Furthermore, models could be used to study the effect of isospin correction.
Another interesting result of NA49 [73] is that when loking at the enhancement of the

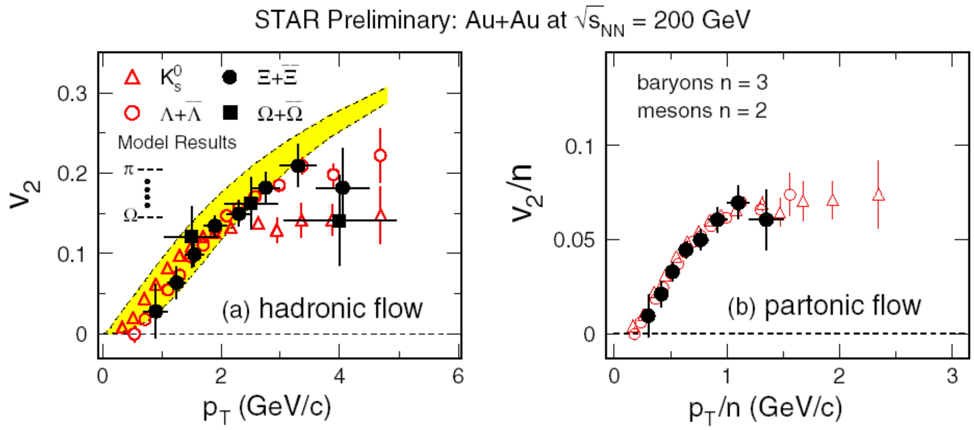

FIGURE 15. Left: The azimuthal anisotropy parameter v2 of strange hadrons as a function of p_T in minimum bias Au+Au collisions at $\sqrt{s}$=200 GeV. The hatched band indicates results from hydrodynamical calculations. Right: the same while both v2 and the p_T have been divided by the number of constituent quarks in each hadron.

projectile component from the p+p expectation (p+A = p+p (0.5 Nr of collisions x alpha + 0.5 E_{proj}, with E_{proj} the enhancement factor and alpha the isospin correction), the Ξ^- and $\overline{\Xi}$ have the same enhancement factor among them and in both Pb+Pb and p+Pb collisions. It would be important to see the Ξ^+ and Ξ^- ratio to participating nucleons or to pions after isospin correction, rather than the above factor E_{proj} to be able to assess the role of this correction.

Selected topics: 4. Comparison to coalescence
A further question is if yields of hadrons including strangeness are compatible with their production by quark coalescence out of a hadronizing QGP. Quark coalescence models predict a universal scaling of elliptic flow parameters versus p_T with the number of constituent quarks. There has been shown recent evidence that dividing v2 and p_t by the hadron quark content leads to a universal curve in the pt dependence of the v2 flow component in agreement with the above expectation (fig. 15) [74].

3. PENTAQUARKS

Several models predict the multiplet structure and characteristics of pentaquarks for example the chiral soliton model, the uncorrelated quark model, correlated quark models, QCD sum rules, thermal models, lattice QCD etc. (e.g. [17, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85]). The current theoretical description of pentaquarks is extremely rich as well as important and usefull for further searches, while it should be noted that it does not lead to a unique picture on the pentaquark existence and characteristics. This fact reflects the complexity of the subject. For example the observed mass splitting between $\Xi^{--}(1860)$ and $\theta^+(1530)$ is unexpected or not allowed by some authors e.g. like the old predictions of the soliton model [86, 17] and expected by others e.g. new calculations of

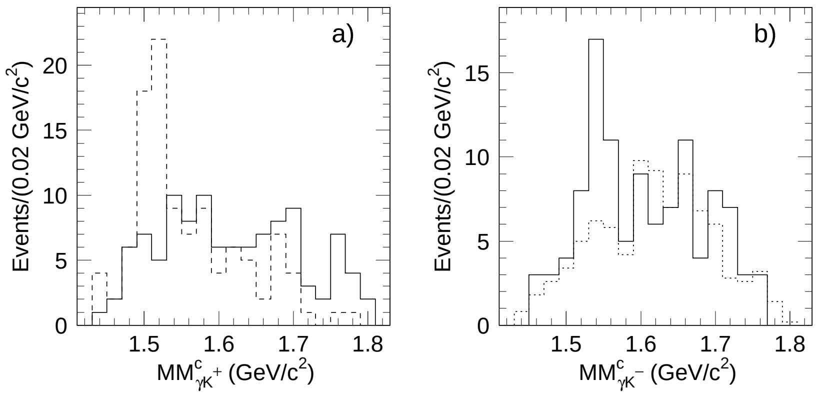

FIGURE 16. Missing mass $M(\gamma,K^+)$ and right of the $M(\gamma,K^-)$ (right) measured by the LEPS Collaboration. See text for explanations.

the soliton model [79, 87]. Furthermore, lattice calculations give very different results to the questions if pentaquarks exist and which mass and parity they have. The revival of the question on pentaquark existence is however very recent, and a fast progress is expected from both theory and experiment in the near future. Here we will concentrate on the experimental results.

$\theta^+_{\bar{s}}$

The first prediction of the mass of the state $uudd\bar{s}$ [16] using the chiral soliton model was m($uudd\bar{s}$) = 1530 MeV. A recent updated study of pentaquarks within this model has shown that this value has a systematic error of the order of $\pm$ 100 MeV [79].

Recent advances in theoretical description of pentaquark characteristics, in particular the prediction of the width of θ^+($uudd\bar{s}$) with spin=1/2 to be below 15 MeV [17] as well as in experimental methods and instrumentation [19] lead to the observation of the θ^+($uudd\bar{s}$) in the $\gamma n \to \theta^+ K^- \to K^+ n K^-$ reaction by the LEPS collaboration. They used γ beam with energy 1.5-2.4 GeV on C and H targets to be able to study γn and γp reactions. They found m(θ^+) = 1540 $\pm$ 10 $\pm$ 5 (syst) MeV, width less than 25 MeV and $S/\sqrt{B}$ = $19/\sqrt{17}$= 4.6. The neutron was inferred by missing mass measurement. Many systematic studies have been performed e.g. for the understanding of the background. Figure 16 shows left the missing mass $M(\gamma,K^+)$, and right of the $M(\gamma,K^-)$. Left the dashed line shows the $\Lambda(1520)$ peak when a proton has been detected due to $\gamma p \to K^+K^-\Lambda(1520)$. The solid line shows the θ^+ selected sample after all cuts, which does not exhibit a $\Lambda(1520)$ peak. Therefore, the "signal" sample is dominated by γn interactions. The right figure shows the missing mass $M(\gamma,K^-)$ for the θ^+ selected sample after all cuts again as solid line and the background with dashed. The θ^+ peak is visible. Among the systematic studies performed were to intentionally missidentify pions as kaons, test if the tails of the $\phi \to K^+K^-$ distribution generate a peak, test if stronger particle identification destroyes the peak, Monte Carlo studies, test if Λ and Σ peaks are

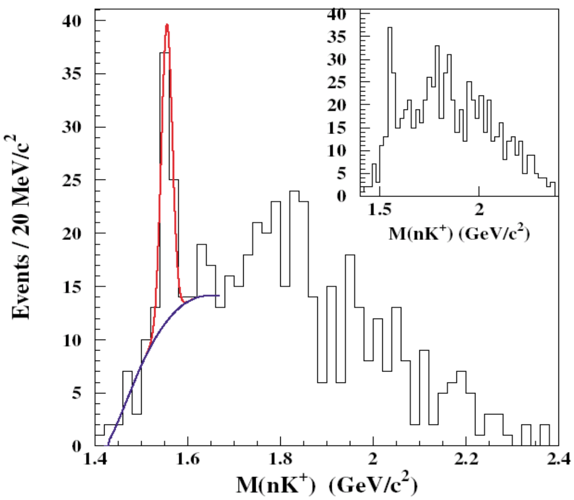

FIGURE 17. Invariant mass nK^+ measured by the CLAS Collaboration. See text for explanations.

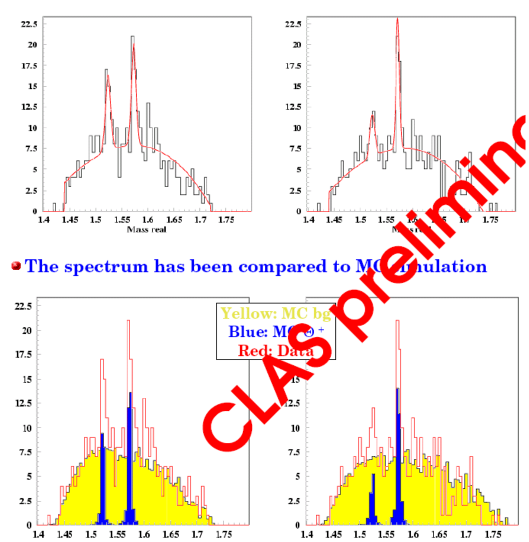

FIGURE 18. Invariant mass nK^+ measured by the CLAS Collaboration. See text for explanations.

well reproduced etc.
Most importantly, recent preliminary analysis of figures.data taken recently by LEPS lead to a confirmation of the seen peak with about 90 entries in the peak above background, as compared to 19 measured previously [88].
This first observation were followed by a number of experiments which have seen the θ^+ peak. The DIANA collaboration at ITEP (bubble chamber experiment) used K^+ beam with energy 850 MeV on Xe and have observed a peak in the invariant mass $K_s^0 p$ from the reaction $K^+ Xe \rightarrow K_s^0 p Xe^{'}$ [23]. They found m(θ^+) = 1539 $\pm$ 2 MeV, width less than 9 MeV and $S/\sqrt{B}$ = 4.4.
The SAPHIR collaboration at ELSA used γ beam with energies 31-94% of 2.8 GeV on

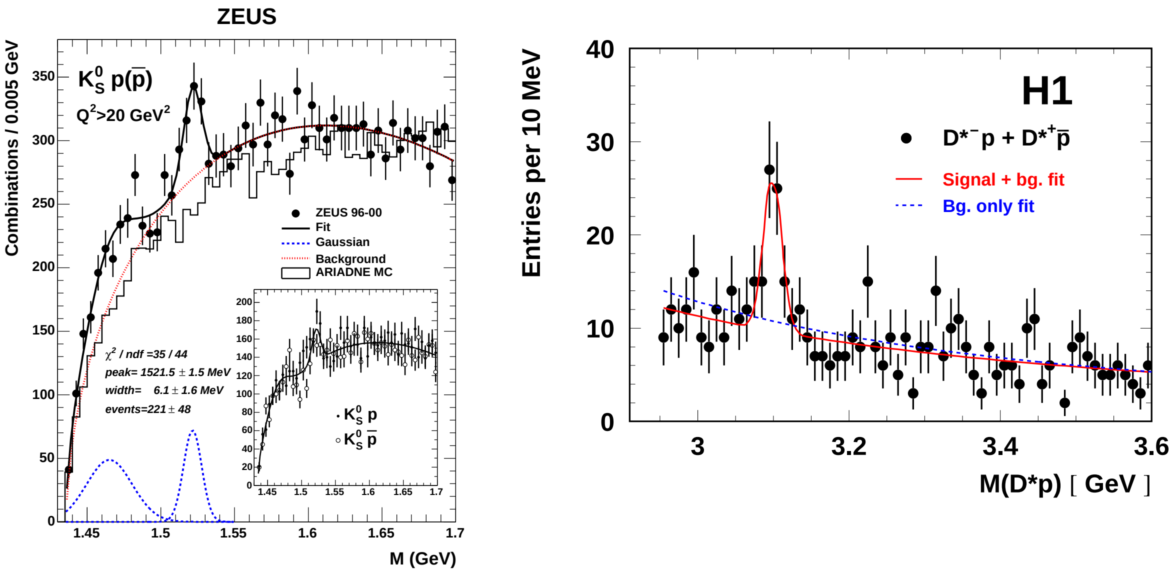

FIGURE 19. Left: Invariant mass $K_s^0 p(\overline{p})$ measured by the Zeus Collaboration. Right: Invariant mass $D^{*-}p$ and $D^{*+}\overline{p}$ measured by the H1 collaboration.

H and have observed a peak in the invariant mass nK^+ from the reaction $\gamma p \to \theta + K_s^0 \to nK^+K_s^0$ [21]. They found m(θ^+) = 1540 $\pm$ 4 $\pm$ 2 MeV, width less than 25 MeV and $S/\sqrt{B}$ = 5.2.
The HERMES collaboration at DESY used e^+ beam with energy 27.6 GeV on deuterium and have observed a peak in the invariant mass pK_s^0 [24]. They found m(θ^+) = 1528 $\pm$ 2.6 $\pm$ 2.1 MeV, width 17 $\pm$ 9 $\pm$ 3 MeV and $S/\sqrt{B}$ = 4.2 to 6.3. While the signal to background ratio in the above publication is 1:3, new analysis lead to an improved signal to background ratio of 2:1 [89].
The COSY-TOF collaboration observed a peak in the invariant mass pK_s^0 from the reaction $pp \to \Sigma^+\theta^+ \to (n\pi^+)(K_s^0 p)$ [27]. They found m(θ^+) = 1530 $\pm$ 5 MeV, width below 18 $\pm$ 4 MeV and $S/\sqrt{B}$ = 5.9. They measure a cross section of 0.4 $\pm$ 0.1 $\pm$ 0.1 (syst) μb which is in rough agreement with predictions of 0.1-1 μb for p+p, p+n near threshold.
An analysis of old ν and $\overline{\nu}$ interactions from old bubble chamber experiments filled with H, d, or neon, and beam energies of 40 or 110 GeV has resulted in a θ^+ peak in the invariant mass pK_s^0 with m(θ^+) = 1533 $\pm$ 5 MeV, width less than 20 MeV and $S/\sqrt{B}$= 6.7 [25].
The CLAS collaboration used γ beam with energy about 95%(2.474-3.115) GeV on deuteron target and have observed a peak in the invariant mass nK^+ from the reaction $\gamma d \to K^+K^-pn$ through missing mass measurement of the neutron [20]. They found m(

θ^+) = 1542 $\pm$ 5 MeV, width of 21 MeV consistent with the experimental resolution, and $S/\sqrt{B}$ = 5.2 $\pm$ 0.6.
In a later publication the CLAS collaboration used γ beam with energy 3-5.47 GeV on deuteron target and have observed a peak in the invariant mass nK^+ from the reaction $\gamma p \to \pi^+ K^- K^+ n$ through missing mass measurement of the neutron (fig. 17) [22]. They observed evidence that the θ^+ is preferably produced through the decay of a new narrow resonance $N^0(2400)$. They found m(θ^+) = 1555 $\pm$ 10 MeV, width less than 26 MeV and $S/\sqrt{B}$ = 7.8 $\pm$ 1. This is the highest published significance obtained for the θ^+ from a single measurement.
A preliminary analysis of CLAS of the reaction $\gamma d \to \theta^+ \overline{K^0} \to (K^+ n) K_s^0$ [90] (fig. 18) shows two peaks in the invariant mass ($K^+ n$) at 1523 $\pm$ 5 MeV and at 1573 $\pm$ 5 MeV both having a width of about 9 MeV and significance of 4, respectively of 6 σ. It is important that CLAS will clarify the reason for the shift of the lower mass peak position and why the second peak appears with the new cuts but not with the old ones in the previously studied reactions. The second peak is a candidate for an excited θ^+ state which is expected to exist with about $\sim$ 50 MeV higher mass than the ground state, in agreement with the observation. A preliminary cross section estimate gives 5-12 nb for the low mass peak and 8-18 nb for the high mass peak. The above two peaks have been quoted also in [91].
CLAS has taken a large amount of data in 2004 which are now been analysed. First results have been quoted which confirm the previous θ^+ observations with new peaks in different channels, all near 1.55 GeV [92].
The ZEUS collaboration at DESY used $e^+ p$ collisions at $\sqrt{s}$=300-318 GeV and have observed a peak in the invariant mass pK_s^0 (fig. 19, left) [26]. They have observed for the first time the $\overline{\theta}^-$ state decaying in $\overline{p}K_s^0$. They found m(θ^+ + $\overline{\theta}^-$) = 1527 $\pm$ 2 MeV, width 10 $\pm$ 2 MeV.
The NA49 experiment has also reported recently a preliminary result of a peak observed in the invariant mass pK_s^0 in p+p reactions at $\sqrt{s}$=17 GeV with mass 1526 $\pm$ 2 MeV and width below 15 MeV [93]. They have also reported a preliminary evidence that the θ^+ peak appears more pronouned after assuming θ^+ production through the decay of a resonance $N^0(2400) \to \theta^+ K^-$ [94] as suggested by CLAS [22] and discussed in [95, 96].
NOMAD has shown recently preliminary results on the observation of a θ^+ candidate peak in the pK_s^0 invariant mass using their full statistics of νA interactions, with a mean energy of the ν beam of 24.3 GeV [28]. The mass observed is 1528.7 $\pm$ 2.5 MeV and the width is consistent with the experimental resolution of 9 MeV.
GRAAL has shown preliminary results on the observation of a θ^+ candidate peak in the pK_s^0 invariant mass in $\gamma d \to \theta^+ \Lambda^0 \to (K_s^0 p) \Lambda^0$ interactions, using γ energy of maximally 1.5 GeV [97]. The mass observed is 1531 MeV while no error is given.

Most of the experiments measure a θ^+ width consistent with the experimental resolution, while few of them give a measurement of width somewhat larger than their resolution namely Zeus and Hermes. A measurement with a much improved resolution would be important.
Non-observation of θ^+ in previous experiments lead to an estimate of its width to be of

the order of 1 MeV or less [98]. This limit would gain in significance, once the θ^+ non-observation by several experiments will be better understood, excluding other reasons for the θ^+ non-observation in the examined reactions.

Do the measured θ^+ masses vary as expected for a real state ?
Figure 20 shows a compilation of the masses of θ^+ candidate peaks observed by several experiments. The statistical and systematic errors (when given) have been added in quadrature. For GRAAL we assume an error of 5 MeV as no error has been given in [97]. For the two preliminary peaks of CLAS we assume the systematic error of 10 MeV quoted previously by CLAS. The lines indicate the mean value of the mass among the $\theta^+ \to pK_s^0$ and the $\theta^+ \to nK^+$ observations. It appears that the mass of θ^+ from $\theta^+ \to nK^+$ observations is systematically higher than the one from $\theta^+ \to pK_s^0$ observations. This may be related to the special corrections needed for the Fermi motion and/or to details of the analysis with missing mass instead of direct measurement of the decay products.
All observations together give a mean mass of 1.533 ± 0.023 GeV and they deviate from their mean with a χ^2/DOF of 3.92. The χ^2/DOF for the deviation of the $\theta^+ \to pK_s^0$ observations from their mean of 1.529 ± 0.011 GeV is 3.76. The χ^2/DOF for the deviation of the $\theta^+ \to nK^+$ observations from their mean of 1.540 ± 0.020 GeV is is 0.94.
The bad χ^2/DOF for the $\theta^+ \to pK_s^0$ observations maybe due to an underestimation of the systematic errors. In particular in some cases no systematic errors are given, sometimes because the results are preliminary. If we add a systematic error of 0.5% of the measured mass (therefore of about 8 MeV) on all measurements for which no systematic error was given by the experiments, we arrive to a χ^2/DOF for the $\theta^+ \to pK_s^0$ observations of 0.95 and a mean mass of 1.529 ± 0.022 GeV. The χ^2/DOF for the $\theta^+ \to nK^+$ observations almost don't change by this, (mean mass = 1.540 ± 0.022 GeV, χ^2/DOF=0.91), because the experiments mostly give the systematic errors for this decay channel. All observations together give then a mean mass of 1.533 ± 0.031 GeV and they deviate from their mean with a χ^2/DOF of 2.1, reflecting mainly the difference of masses between the two considered decay channels. It is important to understand the origin of this discrepancy.
This problem can be studied measuring $\theta^+ \to K^+ n$ in experiments with direct detection of the neutron or the antineutron for the $\overline{\theta^-}$ like PHENIX and GRAAL.

θ^{++}
A preliminary peak is quoted by CLAS [91] for the candidate $\theta^{++} \to pK^+$ produced in the reaction $\gamma p \to \theta^{++}K^- \to pK^+K^-$ at 1579 ± 5 MeV. A previous peak observed by CLAS in the invariant mass pK^+ has been dismissed as due to ϕ and hyperon resonance reflexion [99].
The STAR collaboration quoted a preliminary peak in the pK^+ and $\overline{p}K^-$ invariant masses at 1.530 GeV, with $S/\sqrt{B} \sim 3.8$ and width about 9 MeV, which is candidate for the $\theta^{++} \to pK^+$ as well as the antiparticle $\overline{\theta^{--}} \to \overline{p}K^-$ in d+Au collisions at $\sqrt{s}$=200 GeV [100].

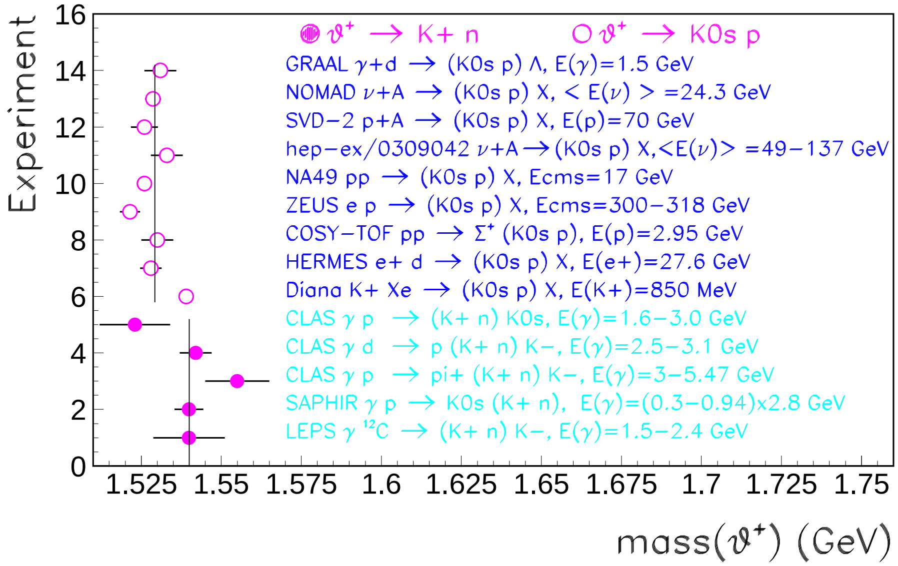

FIGURE 20. Compilation of measured θ^+ masses.

HERMES has reported the non-observation of a peak in the pK^+ invariant masses [24].

Ξ, N^0

The NA49 experiment has observed in p+p reactions at $\sqrt{s}$=17 GeV the pentaquark candidates $\Xi^{--}(1862 \pm 2MeV) \rightarrow \Xi^-\pi^-$, the $\Xi^0(1864 \pm 5MeV) \rightarrow \Xi^-\pi^+$ and their antiparticles [29]. They measure a width consistent with their resolution of about 18 MeV. They also observe preliminary results of the decay $\Xi^-(1850) \rightarrow \Xi^0(1530)\pi^-$ (fig. 21) with simarly narrow width as the other candidates [30]. The Ξ^{--} is a candidate for the antidecuplet and the Ξ^0 too due to the small mass difference while it is unclear if the $\Xi^-(1850)$ is from the octet or the antidecuplet. An observation of the Ξ I=1/2 from the octet in ΛK_s^0 would answer this question. The non observation of a peak in the invariant mass $\Xi^0(1530)\pi^+$ is also an important information, as this decay channel is not allowed by SU(3) for the antidecuplet Ξ^+ [77].
The experiment STAR has shown preliminary results on a N^0 ($uds d\bar{s}$, $uddu\bar{u}$) or Ξ ($uds s\bar{d}$) I=1/2 candidate. The N^0 can be a mixture of the quark contents ($uds d\bar{s}$, $uddu\bar{u}$). STAR uses minimum bias Au+Au collisions at $\sqrt{s}$=200 geV and observes a peak in the decay channel ΛK_s^0 at a mass 1734 ± 0.5 (stat) ± 5 (syst) MeV (fig. 22) with width consistent with the experimental resolution of about 6 MeV and $S/\sqrt{B}$ between 3 and 6 depending on the method used [32]. Extensive systematic studies have been performed, investigating particle missidentifications, split tracks and kinematic reflexions. They also observe signs of the known narrow states $\Xi(1690)$ and $\Xi(1820)$ with a lower significance. They don't observe a peak near 1850 - 1860 MeV resulting from a Ξ^0 I=1/2 (octet) pentaquark state with the same mass as the $\Xi^-(1850)$ of NA49, disfavouring the

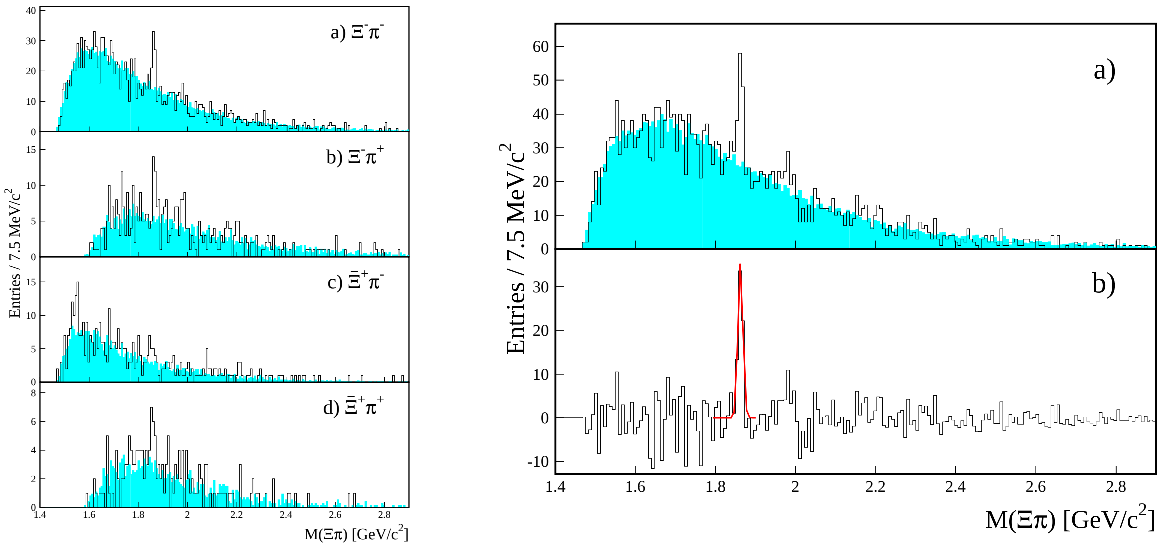

FIGURE 21. Invariant mass $\Xi^-\pi^-$, $\Xi^-\pi^+$ and their anti-channels and their total sum measured by the NA49 collaboration.

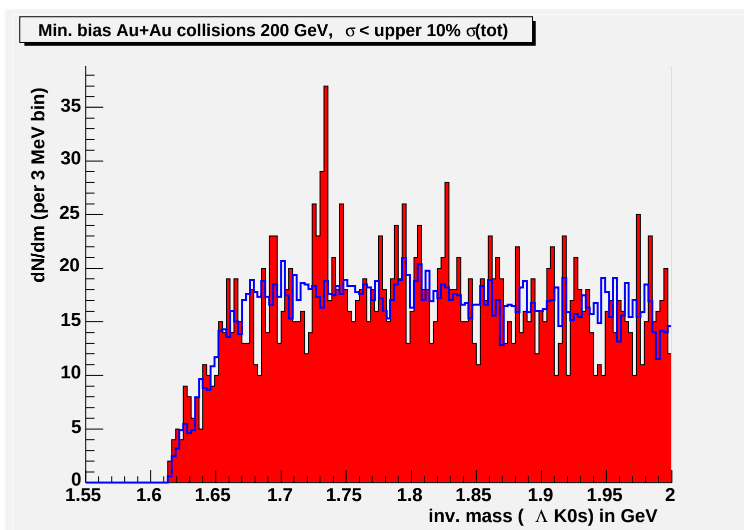

FIGURE 22. Invariant mass ΛK_s^0 measured by the STAR experiment. See text for explanations.

picture of degenerate octet and antidecuplet even though a low branching ratio to ΛK_s^0 may not allow to observe the peak with the present statistics.

The GRAAL experiment has shown preliminary results on two narrow N^0 candidates. One candidate is observed at a mass of 1670 MeV in the invariant mass of ηn from the reaction $\gamma d \to \eta n X$. The neutron has been directly detected. The other is observed at a mass of 1727 MeV in the invariant masses of ΛK_s^0 as well as in the invariant masses of $\Sigma^- K^+$ at the same mass and with the same width [101]. The second reaction allow to establish the strange quark content and therefore to exclude the Ξ hypothesis. The

difference of 7 MeV between the STAR and GRAAL measured masses of 1727 and 1734 MeV, should be compared to the systematic errors. STAR quotes a systematic error of 5 MeV while GRAAL quotes no systematic error.
The mass of the peaks at 1670 and at (1727,1734) MeV is in good agreement with the N masses suggested by Arndt et al [102]. In this paper a modified Partial Wave analysis allows to search for narrow states and presents two candidate N masses, 1680 and/or 1730 MeV with width below 30 MeV.
While the above mentioned narrow N^0 candidates of mass 1670 and 1727-1734 MeV fit well into the picture of the expected N and N_s pentaquark candidates, they can also be something else than pentaquarks, e.g. a new N^0=udd resonance, or a $uddgg$ state. This statement is true for all non-exotic pentaquark candidates.

$\theta_{\overline{c}}^0$
The H1 collaboration at DESY used $e^- p$ collisions at $\sqrt{s}$=300 and 320 GeV and have observed a peak in the invariant masses $D^{*-}p$ and $D^{*+}\overline{p}$ (fig. 19, right) at a mass 3099 $\pm$ 3 (stat) $\pm$ 5 (syst) MeV and width of 12 $\pm$ 3 MeV [31]. The probability that the peak is a background fluctuation is less than 4 10^{-8}. Extensive systematic studies have been performed. The momentum distribution of the signal is as expected for a particle at this mass. This peak is a candidate for the state $\theta_{\overline{c}}^0$ = $uudd\overline{c}$ and is the first charmed pentaquark candidate seen. The mass and width of the particle and it's antiparticle are consistent.

Non-observations
Several experiments have reported preliminary results on the non-observation of pentaquarks e.g. e^+e^-: Babar, Belle, Bes, LEP experiments, $p\overline{p}$: CDF, D0 pA:E690, eA: HERA-B, ep: Zeus (for the θ_c^0) [103].
It has been argued that the non-observation of pentaquark states in the above experiments is due to an additional strong suppression factor for pentaquark production in $e+e^-$ collisions, as well as in B decays which is lifted in reactions like γA in which $s\overline{s}$ and a baryon are present in the initial state [95]. The constituents of the θ^+ are already present in the initial state of e.g. low energy photoproduction experiments, while in other experiments baryon number and strangeness must be created from gluons [95]. The penalty for their production could be estimated from data e.g. $\overline{d}/\overline{p}$ ratios [95]. It is important to try to assess the expected cross sections [104].
The CDF ($p\overline{p}$) and E690 (pA) non observation of pentaquarks can be a consequence of the decrease of the pentaquark cross section with increasing energy [105, 106]. This depends however on the kinematic region considered, and it is suggested to look for pentaquarks in the central rapidity region [105, 106].
In addition, if the θ^+ is produced preferably through the decay of a new resonance $N^0(2400) \to \theta^+ K^-$ as suggested by CLAS and NA49 and as discussed in [95, 96], neglecting this aspect maybe a further cause of its non-observation in some experiments. Some authors point out the importance to exclude kinematic reflexions as reason behind the θ^+ peak [107]. This known source of systematic errors is investigated by the experiments which observe pentaquark candidates. Other authors discuss limits from the non observation of the $\Xi(1860)$ peaks of NA49 by previous experiments [108]. These points are addressed while trying to explain the new non-observations of pentaquarks quoted

above.

There were also rumors spread around in the physics community in particular e.g. a e^+e^- experiment has found that a certain error in the identification of particles can lead to a peak in the $D^{*-}p$ invariant mass near 3.1 GeV faking the θ_c^0 candidate of H1. However H1 is aware of this fact and at which conditions it appears, and the fake peaks have been carefully excluded. This shows that it is important to document all findings and examine all evidence.
It can certainly happen that a systematic error can lead to a peak coinciding with the real one or the expected one, in which case it may be missinterpreted. Another example is PHENIX which presented a peak at 1.540 GeV in the $\overline{n}K^-$ invariant mass, candidate for the $\overline{\theta^-} \rightarrow \overline{n}K^-$ which has been later understood to be due to a calibration error [109].

It is clear that a higher statistics is desirable in order to confirm the pentaquark observations reported so far, as well as more measurements and searches by other experiments. New data taken in 2004 and planned to be taken in 2005 will lead to enhancements in statistics of experiments up to a factor of 10 allowing to test the statistical significance and make more systematic studies. Experiments searching for pentaquarks should test also the production mechanisms proposed in the literature e.g. the θ^+ production through the $N^0(2400)$ decay. For example Phenix could search for the final state $\overline{\theta^-}K^+$ or $\overline{\theta^-}K_s^0$ demanding the invariant mass of $\overline{\theta^-}K_s^0$ and $\overline{\theta^-}K^+$ to be in the range 2.3 to 2.5 GeV, and study the option to trigger online on this channel.
Furthermore, not only the observations of pentaquark candidates but also the non-observations should be published and be well documented in order to facilitate a better understanding of the underline physics.

4. SUMMARY AND CONCLUSIONS

4.1. Strangeness

An enhancement in the strangeness to pion ratio has been observed in A+A collisions with respect to p+p and p+A collisions at the same energy. A spectacular enhancement has been measured especially in strange baryon and antibaryon production per participant nucleon (N) in A+A collisions at SPS and RHIC as compared to p+A collisions at the same energy. However this enhancement increases with decreasing energy, disqualifying it as QGP signature. This behaviour can be understood as due to the fact that at the same energy p+p , p+A and A+A collisions reach a different initial temperature (T), energy density (ε_i) and μ_B, or deviate from equilibrium, rendering their comparison inadequate.
A new parameter adequate to compare strangeness in different colliding systems, the initial energy density (ε_i) has been introduced. This is the only parameter characterizing the initial state of the collisions which can be estimated from the data.
We consider in the following only systems which agree with a grandcanonical description e.g. mainly central A+A collisions but also elementary collisions like $p\overline{p}$ collisions.

Studying the energy dependence of the total $s\bar{s}$ production through the strangeness suppression factor λ_s we find two dependences which overlapp each other. The one is the dependance of λ_s on μ_b. The other is the dependence of λ_s on T.
After eliminating trivial sources of strangeness enhancement, like comparing systems with different μ_B and ε_i we arrive at a universal behaviour of λ_s in central A+A and particle (e.g. $p\overline{p}$) collisions.
In particular λ_s at $\mu_B = 0$ is simply following the temperature rising as a function of ε_i and saturating above $\varepsilon_i \sim$ 0.6-1 GeV/fm3. This is plausible, as λ_s is one of the particle ratios which enters the very determination of T, and is also strongly T dependant. It is more sensitive to μ_B as the T which is estimated through several ratios, some of them less sensitive to μ_B than the λ_s ratio.

Strangeness (and temperature) enhancement is therefore observed in a dramatic way for all systems reaching an ε_i greater than 0.6-1 GeV/fm3 as compared to all systems with smaller ε_i. This indicates the onset of the phase transition at 0.6-1 GeV/fm^3 in agreement with the ε_i(crit) predicted by lattice QCD estimates. The latest fit to data gives ε_i(crit) $\sim 0.6 \pm 0.2 \pm 0.3$ (syst) GeV/fm^3. More data will allow for a more precise estimate of ε_i(crit).
Note that all above observations are made using hadrons with u,d,s quarks and their antiquarks. We therefore can speak about a light flavoured QGP. The outstanding feature of strangeness production taken together with light flavoured hadrons is that they allow to estimate the critical parameters, unlike hard probes like $c\bar{c}$, $b\overline{b}$ states suppression, and jet quenching which may be setting in above T_c. Correlation of onsets seen in other features of light flavoured hadrons like flow [110], study of spectral characteristics [111], or fluctuations as a function of energy will enhance the accuracy of this estimate.
On the other side, if one argues that the dramatic rise and saturation of T (and λ_s) after $\varepsilon \sim$ 0.6-1 GeV, has nothing to do with the QCD phase transition, also strangeness enhancement has nothing to do with the QCD phase transition.

It is an ongoing discussion in the literature what the saturation of the chemical freeze out T with increasing energy really means and especially why is the same for p+p and A+A collisions e.g. [61, 62, 63].
It is always taken for granted that no QCD phase transition can appear in a p+p system due to the small volume. What if the p+p system has infinite energy ? After which energy the initially colliding particle volumes plays no role anymore ?
Maybe it is not a completely unexpected feature, if the hadronization of any quark and gluon system into hadrons (e.g. jet hadronization), as well as the hadronic mass spectrum, do reflect the existance and value of the T_c of the QCD phase transition. A "QCD phase transition" in a high multiplicity $p\overline{p}$ collision ? [64] Along a hadronizing jet ? [65].
While $q\overline{q}$ produced in an elementary collision fly apart and cannot communicate with each other [62], the hadronization along each jet and the resulting particle yields may exhibit equilibrium features reflecting the T_c. Maybe it is the QCD vacuum itself which has a thermostat-like nature [62].
However, $p\overline{p}$ collisions, like A+A collisions too, need a centrality trigger to result in grandcanonical particle ratios e.g. at midrapidity.

How can a high multiplicity $p\overline{p}$ collision appear to be an equilibrated system? We elaborate on the consequences of quantum mechanical coherence for multiparticle production [62] [63].
High energy particle collisions should not be viewed as a classical billiard ball cascade. Interactions among particles and virtual particle exchange for a quantum mechanical coherent system may lead faster to equilibrium.

Figure 9, right, shows evidence of a universal behaviour of λ_s in both A+A and $p\overline{p}$ collisions. The same universality is seen for the temperature (fig. 14).
One could make these plots and extract T_c using simply high multiplicity $p\overline{p}$ collisions ? This is to be proven. We see however already the same tendency in the N+N data in fig. 6, right, even if these data have not been tested against thermodynamic behaviour.
Evidently, A+A collisions offer additional crucial means to learn about the QCD phase transition through phenomena like $c\overline{c}$, $b\overline{b}$ suppression, jet quenching, flow effects, fluctuations etc. Flow of strange particles seem to agree with production through quark coalescence.
It appears that many open problems need to be clarified in order to arrive in a clear all encompassing picture of the QCD phase transition in nature. Future precision measurements of hadrons at RHIC and the LHC in both A+A and p+p collisions will considerably improve our understanding of strangeness and its role in the QCD phase transition. Questions about deviations from equilibrium will be better addressed through presence of precise and abundant data. RHIC and LHC data from A+A as well as p+p and p+A collisions, and low energy measurements around 30 A GeV Pb+Pb at SPS and the future GSI will be crucial for measuring the critical T with a high accuracy, possibly learn about the order of the transition and other characteristics and detect new critical phenomena like fluctuations.

4.2. Pentaquarks

The theoretical description of pentaquarks is advancing very rapidly, however it does not lead to a unique picture on the pentaquark existence and characteristics, reflecting the complexity of the subject. For example, different lattice calculations give very different results to the questions if pentaquarks exist and which mass and parity they have. The narrow width of θ^+ remains to be understood, as well as it's production mechanism and $\sqrt{s}$ dependence. The revival of the question on pentaquark existence is however very recent, and a fast progress is expected from both theory and experiment in the near future.
Many experiments observed the θ^+ ($uudd\overline{s}$) peak in different reactions and energies and in two decay channels namely into nK^+ and into pK_s^0. The systematic errors of each channel differ as well as the backgrounds. The mass of θ^+ from nK^+ measurements is systematically higher than the mass from pK_s^0, which may be due to Fermi-motion corrections and the details of missing mass analysis as compared to direct measurements. If we add a systematic error of 0.5% of the measured mass (therefore of about 8 MeV) on all measurements for which no systematic error was given by the experiments, we

find that the θ^+ mass from $\theta^+ \to pK_s^0$ deviate from their mean mass of 1.529 $\pm$ 0.022 GeV with a χ^2/DOF of 0.95. The θ^+ mass from $\theta^+ \to nK^+$ for which the systematic errors are given, gives a mean mass of 1.540 $\pm$ 0.022 GeV and a χ^2/DOF=0.91. All observations together give a mean θ^+ mass of 1.533 $\pm$ 0.031 GeV and they deviate from their mean with a χ^2/DOF of 2.1, reflecting mainly the difference of masses between the two considered decay channels. It is important to understand the origin of this discrepancy.

The largest individual $S/\sqrt{B}$ was 7.8. This suggests that an increase of significance is needed to make this result more reliable. New data taken by the CLAS and LEPS experiments in 2004, confirm in a preliminary analysis the θ^+ peak, suggesting that the hypothesis of a statistical fluctuation is not probable. The possibility of systematic errors need to be excluded.
Neutrino experiments (which have seen the θ^+) due to their full acceptance and the clean reaction should be more free of bias of the type of kinematic reflexions than restricted acceptance and/or high multiplicity experiments.
The antiparticle $\overline{\theta}^-$ has also been observed with mass and width consistent with the θ^+ peak by Zeus.
Most of the experiments measure a θ^+ width consistent with the experimental resolution, while few of them give a measurement of width somewhat larger than their resolution namely Zeus and Hermes. A measurement with a much improved resolution would be important. Non-observation of θ^+ in previously taken experimental data lead to an estimate of its width to be of the order of 1 MeV or less [98]. This limit would gain in significance, once the θ^+ non-observation by several experiments will be better understood.
Preliminary CLAS results exhibit a second peak in the nK^+ spectrum suggesting an excited state of θ^+. In addition, there is evidence that the θ^+ is preferably produced by the decay of a new resonance $N^0(2400)$. There are also preliminary hints for a peak in the pK^+ and $\overline{p}K^-$ invariant masses by STAR and CLAS, however at a different mass of 1.53 and 1.57 GeV.

The NA49 experiment observed narrow candidates for the $\Xi^{--}(1860)$ ($ddss\overline{u}$), $\Xi^0(1860)$ ($uuss\overline{u}$) and $\Xi^-(1850)$ ($dssu\overline{u}$) pentaquarks and for the antiparticles of the first two. A detailed discussion of θ^+ and the Ξ^{--} (called $\phi(1860)$) have been added recently in the Review of Particle Physics under exotic baryons [14]. It is entitled θ^+, a possible exotic baryon resonance and has three stars. The mass of the $\Xi(1860)$ is in agreement with the most recent estimates of the chiral soliton model unlike earlier work [79].

The H1 experiment has observed a candidate for the first charmed pentaquark the $\theta_c^0(3099)$ ($uudd\overline{c}$) with width of 12 $\pm$ 3 MeV and it's antiparticle. The mass and width of the particle and it's antiparticle are consistent.

The STAR experiment has observed a N^0 ($udsd\overline{s}$, $uddu\overline{u}$) or Ξ ($udss\overline{d}$) I=1/2 candidate with mass 1734 MeV in Au+Au reactions at $\sqrt{s}$=200 GeV in the ΛK_s^0 invariant mass,

and width consistent with the experimental resolution of about 6 MeV. The GRAAL experiment has reported two narrow candidates for N pentaquarks namely at 1670 in the ηn invariant mass and at 1727 MeV in the ΛK_s^0 and the $\Sigma^- K^+$ invariant masses. The observation of the 1727 MeV peak in two decay channels with same mass and width, reduces considerably the probability that the peak is due to a kinematic reflexion or other systematic error, as the sources of systematic errors and the background is different for the two decay channels studied. The mass of the peaks at 1670 and (1734, 1727) MeV are in good agreement with the N mass of $\sim$ 1670, 1730 MeV suggested by a modified partial wave analysis of old data by Arndt et al [102].

Furthermore, several high statistics experiments report the non-observation of pentaquark states in particular inclusive studies of e^+e^- collisions, B decays, and inclusive high energy $p\overline{p}$ and pA reactions. Recent publications discuss problems like e.g. the non-observation of these peaks by previous experiments [108] and the possibility that the observed peaks are kinematic reflections e.g. [107]. This source of systematic errors is investigated by the experiments which observe pentaquark candidates. As non-observations are concerned the characteristics of the θ^+ production mechanism may be one reason why this state has not been observed in a number of experiments [95, 96]. Non-observations in high statistics e^+e^- experiments in B decays and high energy $p\overline{p}$, pA experiments, may be due to pentaquark cross section suppression in e^+e^- reactions as well as at high energy [105, 106]. The increase in statistics planned by several experiments will allow to test the current observations with a much better significance and will allow also a better study of systematic errors, as well as a measurement of pentaquark characteristics like the parity and the spin. Furthermore, not only the observations of pentaquark candidates but also the non-observations should be published in order to facilitate a better understanding of the underline physics.

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